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Stealth on Aircraft; A Literature Review

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ABSTRACT: The research and development of stealth aircraft has sped up in the last decades. The main change is the switch from a coating based stealth layer to a fiber mat, which has a multitude of advantages. The stealth technology currently in development combines a radar absorbing material with clever shaping of the plane in order to keep the radar cross section as low as possible. The technology that has been developed now has the ability to reduce the radar cross section of a F-35 fighter jet to the size smaller than a bird if it were to be picked up by a radar. The older types of stealth relied on a coating based approach, of which multiple types are proposed in this paper and a comparison is made based on the reflection loss (RL) of said coatings. Lastly a conclusion can be made that complex permeability, thickness, complex permittivity and intrinsic impedance of the used material influence the performance of the stealth coating.

Key words: Aircraft, Stealth Coating, RAM, Reflection Loss

1 INTRODUCTION

In modern day warfare it is essential to obtain air superiority. When the air above a disputed territory is secured, high value targets can be taken out without the high risk of sending in ground troops. A relevant example is the war between Russia and Ukraine, Russia has been struggling to advance due to a multitude of factors. One of these factors is the fact that they can not get air superiority due to the western launchers and anti-aircraft weapons that are being supplied to the Ukrainian army. In order to obtain air superiority it is crucial for a fighter plane to stay hidden from radars and perform better than their adversary in air to air combat. One of the ways in which this battle can be turned into one sides favor is by making use of the element of surprise. However, with the introduction of stronger and higher ranged radar systems the need for a good stealth coating on an aircraft has become absolutely crucial for winning these fights. Countries are constantly in a race to develop the next generation stealth aircraft that can remain unseen by radars in order to operate in enemy territory. But how can the difference in stealth performance from different generation aircraft be explained? This research paper investigates the stealth technology and answers the following research question;

When applying stealth coating to an aircraft, what are important parameters to take into consideration when creating such a coating and how do they affect the stealth performance of these aircraft?

This research question will be answered by the use of several sub-questions, which will be answered throughout different sections of this paper.

1. Why is stealth coating applied on aircraft?
2. How does a stealth coating work?
3. What is the difference between multiple types of stealth coating?

To answer these research questions multiple articles were used, these articles were found with the use of Scopus and various other research methods.

2 THE USE OF STEALTH ON AIRCRAFT

During the 1930's the first radar technologies were developed by countries around the world in response to the first world war and the increase in plane usage [1]. This naturally sparked the interest for fighter jet manufacturers around the world to find a way to circumnavigate these radars to avoid detection. The first aircraft that actually possessed stealth technology was the Lockheed F-117A seen in Figure 1, which became operational in October of 1983. The way that



Fig. 1: F-117A Nighthawk developed by Lockheed

this aircraft was made contributed to the stealth properties. For instance, the panels of which the airplane consisted were placed in such a way that reflection of radar waves was either directed in a different direction than back to the radar. One article [1] calls it "unlikely" that the aircraft is detected in more than one radar sweep due to this geometry. A quote from the article reads;

"The rationale of the faceting technique is to eliminate random and isotropic scattering features, as far as possible, from the aircraft's shape. The flat surfaces have a signature profile with a relatively strong peak when illuminated by a radar beam which is normal to the surface, but the return weakens rapidly at small angles away from normal. No two surfaces lie in the same plane, and all of them are angled so that the chances of a ground-based or airborne radar illuminating them at a normal angle are very small." [1]

Another stealth aspect of this aircraft was the addition of a ferrite active ingredient in a polymer base. This is said to absorb some of the radar waves that reach the plane and therefore reduce the feedback signal that reaches the radar system on the ground. This Radiation-absorbent material (RAM) is being applied by different materials with varying thickness but all serve the same purpose; let the radar waves hit the surface of the plane and then convert this energy into heat instead of bouncing them back towards the radar installation. A further explanation on this technology is given in section 3

For the United States Air Force (USAF) the F-117A was a prove of concept that stealth was a viable

option for aircraft and development of other stealth aircraft was given the green light. This resulted in one of the most known examples of a stealth aircraft, namely the B-2 bomber (Figure 2)

The reasons why this stealth aircraft works is explained based on three stealth aspects, which are explained in further detail in sections 2.1, 2.2 and 2.3



Fig. 2: B-2 Stealth Bomber developed by Northrop Grumman

2.1 Plane orientation

To understand the importance of the orientation of the planes on the airplane it is essential that there is a basic understanding of a conventional radar. The way that a conventional radar works is that an energy wave is being transmitted from a source, the radar switches to receiving mode and waits for a signal that bounced back from whatever it is the radar is trying to detect. Based on the strength of a signal that bounced back from the object its size can be determined. A measure of a target's ability to reflect radar signals in the direction of the radar receiver is referred to as the radar cross section [3]. For instance, the B-2 bomber, which has a wingspan of 52 meters, has been reported to have the same radar cross section as a large bird [3]. This is mainly due to its shape. As can be seen in Figure 2, the wings are not straight but angled. This causes the radar waves, if directed from the front, to be scattered towards either side of the plane instead of back towards to receiver. This is illustrated in Figure 3

Whilst this may seem like a very good option it must be noted that radars almost never consist of only one station. In general multiple substations share their data with each other and based on this data calculate if there is an object in the sky. Therefor bouncing the waves back into different directions in comparison to the original directions might still result in the plane

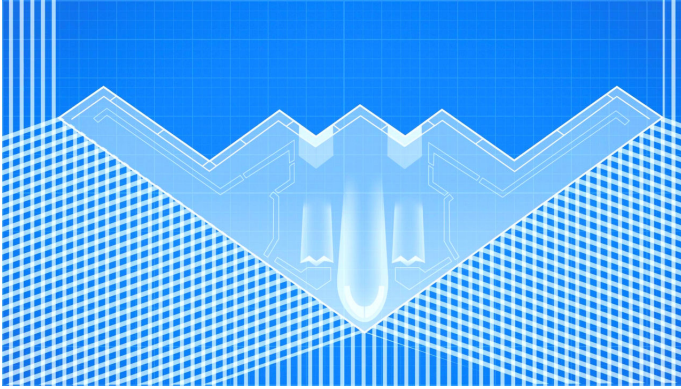


Fig. 3: B-2 Bomber reflection [4]



Fig. 4: Clear image of engine placing on a B-2

being detected by another radar installation.

2.2 Coating

In section 1 a short introduction was done to Radiation Absorbing Materials (RAM). These materials have the function of absorbing radiation and transferring this energy into heat. The way this coating works is explained in this section.

A radar wave is essentially a wave of energy, which, if it comes into contact with a surface, interacts with this surface. On most surfaces this energy packet bounces right off due to the surface not being able to absorb this extra amount of energy that is suddenly subjected to it. The paint that is used on the B-2 contains tiny particles of iron, these are oriented in such a way that they generate a magnetic field. When the radar waves hit the surface this results in oscillations of the tiny iron balls resulting in the energy being dissipated into heat instead of being bounced back to the surface [2]. Using these types of coatings can therefore reduce the amount of energy (radar waves) that is being bounced back from the plane.

2.3 Engine placement

The B-2 used the same principles as the F-117A but on a larger scale. In addition to the applied RAM coating and inclined planes to prevent radio detection another precaution taken with this plane was to place the engines on top of the plane. This can be seen in figure 4

With normal aircraft the air right behind the engine leaves a large heat trail leading directly from the engine which can help with the detection of such air-

craft. With this plane the wings, with their radiation absorbing coating prevent detection from such heat seeking systems by having the hot air come out on top of the aircraft. This allows the aircraft to remain undetected by hostile radars.

3 RADIATION ABSORBING MATERIALS

As mentioned in section 2.2 one of the tools to obtain an aircraft with a low radar cross section is the application of a RAM coating. Whilst the exact composition of these coatings is classified there is a general consensus in the literature as to what types of materials are used in the coating and how this affects the performance of the aircraft.

The main ingredient of the coating is a polymer matrix which has ferromagnetic particles embedded into it [5]. A popular RAM is iron ball paint. This type of paint contains small balls which are coated in metal and injected into an epoxy-based paint, which can be applied on the exterior of the plane. The spheres are coated with ferrite or carbonyl iron. [5]. When electromagnetic radiation enters iron ball paint it is absorbed by the ferrite or carbonyl iron molecules which causes them to oscillate. This oscillation reduces with the release of heat. The resulting heat from this process is dissipated into the frame of the airplane.

The solution proposed above can be combined with a smart geometry in order to obtain an object with an even lower radar cross section (RCS). For instance a triangular shape bounces the radar waves multiple times within the triangles before it bounces back to the receiver. When applying the RAM and tiny triangular structures within the paint the radar waves bounce through the RAM multiple times, reducing the radar

waves enough in strength to be barely visible if the radar waves reach the receiver. An illustration of such a composition can be seen in Figure 5

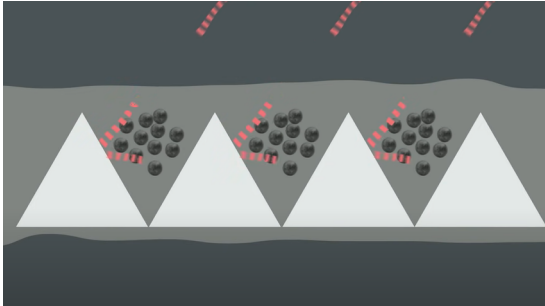


Fig. 5: Dissipation of radar waves [2]

3.1 Requirements

When a material is selected for the coating on aircraft that use stealth coating a multitude of requirements can be drafted, which should all be thought of during the material selection. These requirements are listed in this section and explained where necessary.

- The material should be lightweight
- The material should have good resistance to extreme temperatures
(Operating temperatures from -60°C to $+60^{\circ}\text{C}$ [6])
- The material should have high reliability
- The material should be durable
- The material should not intervene with the aerodynamic performance of the aircraft
(Certain material orientations may cause a loss in aerodynamic performance)
- The material can not corrode, e.g. should be able to deal with extreme weather conditions
- The material should have high friction resistance
(Due to the high speeds the air causes friction with the outside layer of coating)
- The material should be radiation resistant
(Up in the atmosphere radiation values are substantially higher)

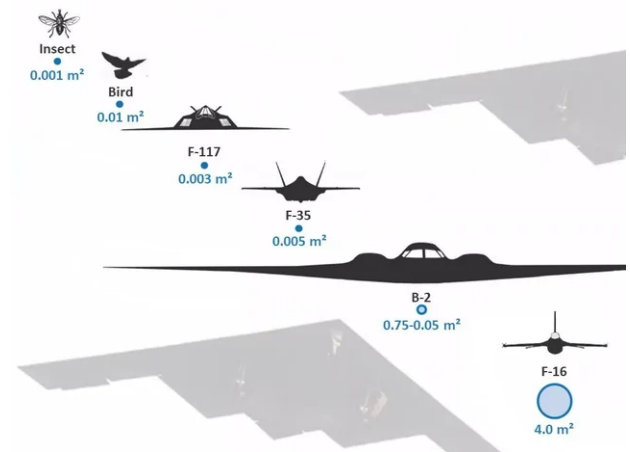


Fig. 6: Radar Cross sections for various objects [19]

3.2 Performance

The materials that are chosen for the coating on stealth aircraft are, understandably, highly classified. However there are estimates on the RCS of different types of military aircraft and ships which are coated with RAM and designed in a way to reduce the RCS to the best of the military's ability. Some RCS's of known planes can be found in Table 1

Target	RCS (m^2)
B-52 Stratofortress (Bomber)	100-125
F-16A (Fighter plane)	5
B-2 Spirit (Bomber)	0,1 or less
F-117A Nighthawk (Fighter)	0,025 or less
Bird	0,01
F-35 Lightning II	0,0015-0,005
F-22 Raptor	0,0001 - 0,0005
Insect	0,001

Table 1: RCS's of military vehicles (estimations based on references [7] to [13], actual values are highly classified)

In Table 1 it can be seen that the RCS of the modern jets is near impossible to distinguish from insects when using radar systems. A visualization of this graph can be seen in Figure 6. What can be seen when comparing Figure 6 to Table 1, is that the values do not completely overlap. A possible explanation for this would be that the actual RCS's of the listed planes are highly classified.

For the F-35 fighter plane the composition of the coating is of course, classified. After an extensive

search of the internet one alleged article could be found in which the executive vice president of the F-35 program gave the following quote: [14]

”It is called ”fiber mat,” and Tom Burbage, executive vice president of F-35 program integration for Lockheed Martin says it is ”the single, biggest technological breakthrough we’ve had on this program.”

The article continues: ”He says that a new process to blend stealth qualities into composite material avoided the need for stealthy appliqué and coatings. Using a new process, Lockheed officials are curing the stealthy, fiber mat substance into the composite skin of the aircraft, according to Burbage. It ”makes this airplane extremely rugged. You literally have to damage the airplane to reduce the signature,” he said in an interview with Aviation Week in Fort Worth. This top-fiber mat surface takes the place of metallic paint that was used on earlier stealthy aircraft designs. The composite skin of the F-35 actually contains this layer of fiber mat, and it can help carry structural loads in the aircraft, Burbage adds. Lockheed Martin declined to provide further details on fiber mat because they are classified. But the disclosure of this new substance comes at a time when Lockheed Martin officials are arguing that maintenance costs for the F-35 will be lower than anticipated by operators” [14]

The original article where this publication refers to has since been deleted so it can not be verified whether this is actually what was mentioned. It would however explain the further decrease of the RCS of the F-35 in comparison to previous generation aircraft. A coating is rather difficult to evenly distribute along a surface and even the slightest imperfections can cause a major spike in radar visibility of a plane. If a pre-made mat can be attached to the outside of a plane this eliminates that chance for imperfections and an added benefit would be that the maintenance costs can be reduced as mentioned by the article [14]. This is due to the fact that a paint layer needs re-coating after a certain amount of time if subjected to harsh conditions. When a fiber mat is attached to the plane the wear is drastically reduced and repairing times (if needed at all) are reduced.

4 DETAILED EXPLANATION RAM

The fiber mat mentioned in section 3.2 most likely also uses a form of radiation absorbing materials. Since this seems to be a recurring property of stealth this section is dedicated to explain, in detail the exact workings of such materials.

4.1 Build-up

A typical coating of a stealth fighter consists of multiple layers which all serve different functions. The inner layers function mostly as protection for the electronics and the material of which the main frame is made. The outer layers are usually the part of the coating that consists of contains the RAM. This coating is built up using multiple layers of RAM coating to ensure that the required RCS reduction is achieved. The new F-35, as previously mentioned, uses a new fiber mat instead of multiple layers of coating. One could imagine that it would be beneficial to have as few layers as possible to keep the weight of the plane low, which results in higher speeds, larger range and better manoeuvrability.

4.1.a Microwave Absorption

The maths behind the absorption of radar waves is a well-researched subject, yet still not completely understood by researchers. They have however come up with a mathematical formulation which can calculate the reflection based on multiple variables such as the t_i , thickness, ϵ_i , complex permittivity (energy storage), μ_i , complex permeability (high frequency magnetic effects), z_i , intrinsic impedance (describes the magnitude of the magnetic and electric fields present) and γ_i is the complex propagation factor of the i^{th} layer. This last value, the γ_i is calculated by the use of a formula which uses the working frequency, propagation velocity as well as a few material properties. The equation that follows from this is denoted in Equation 1

$$\Gamma = \frac{\frac{\sqrt{\mu_1/\epsilon_1} \tanh(\gamma_1 t_1) + \sqrt{\mu_2/\epsilon_2} \tanh(\gamma_2 t_2)}{1 + \sqrt{\mu_1 \epsilon_2 / \epsilon_1 \mu_2} \tanh(\gamma_1 t_1) \tanh(\gamma_2 t_2)} - 1}{\frac{\sqrt{\mu_1/\epsilon_1} \tanh(\gamma_1 t_1) + \sqrt{\mu_2/\epsilon_2} \tanh(\gamma_2 t_2)}{1 + \sqrt{\mu_1 \epsilon_2 / \epsilon_1 \mu_2} \tanh(\gamma_1 t_1) \tanh(\gamma_2 t_2)} + 1} \quad (1)$$

In this equation Γ equals the reflection coefficient of the layer composition. What one can see is that this equation expands to very complicated levels when adding a multitude of layers, which can be visualized in Figure 7.

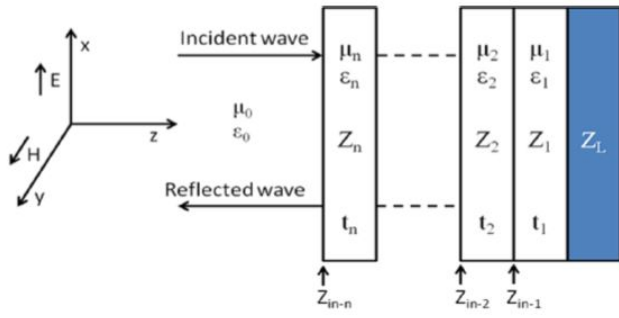


Fig. 7: Multi-layer absorption

The actual reflection loss can be calculated by the use

$$Reflectionloss(dB) = -20 \log_{10} |\Gamma| \quad (2)$$

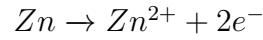
A high reflection loss means that of the incoming radar waves a lot of energy is dissipated within the materials thus only a small fraction of the initial radar wave radiates back towards the outgoing radar source. What can be concluded from the formula stated in Equation 1 is that the reflection coefficient depends on the factors mentioned in this section thus these can be identified as affecting the stealth properties of aircraft.

4.2 Ferrite ingredient

The exact composition of the RAM coating is highly classified, but one article [15] mentions compositions which result in a high reflection loss and an increase in bandwidth. One of these compositions is $BaFe_{12}O_{19}$, a combination of barium, iron and oxygen. From further research it was found that adding certain metallic elements the reflection loss increases further.

Meshram et al. [16] in 2004 reported the design, development and characterization of $BaCo_{0.5d}Ti_{0.5d}Mn_{0.1}Fe_{(11.87-d)}O_{19}$ and $Ba(MnTi)_dFe_{(12-2d)}O_{19}$ hexagonal ferrites ($d = 1.6$) as a wave absorber. The ferrites were developed by the use of the dry attrition method and 60% by weight has been mixed in epoxy resin to observe microwave absorption. It is found that the broadband characteristics with minimum absorption of -9 dB from 8.7 to 10.2 GHz for a coating thickness of 2 mm for two layer absorber. Later on in the article the author mentions a reduction loss (RL) of -39.22dB at 10.88GHz. This is achieved by doping cobalt in

$BaFe_{12}O_{19}$ which results in $BaCo_xFe_{12-x}O_{19}$ with x being variable and chosen as 0, 0.2, 0.4, 0.6, 0.8 and 1. From this research it was found that the doping in cobalt increases the maximum value of both the absorption and bandwidth. The same treatment procedure can be done by using other metallic elements such as Al, Ni, Cr, Ti and Zn. The reason for this is that these metallic elements add free electrons to the coating, which increases the absorption rate of the coating. The reason for this is the presence of the oxygen. When for instance Zn oxidizes electrons are freed according to the following equation



These two free electrons, according to Kumar et al. [15], "Increase the charge at the metal dielectric interface and raise the space charge polarization which affects the conductivity. Therefore, the complex permittivity values of the composites increases due to improved conductivity" [15]. An increase in complex permittivity means an increase in energy storage within the material itself. This is beneficial for RAM coatings since this energy can be used to absorb radar waves.

4.3 Maintenance

Maintenance is an important factor when it concerns fighter planes. It is easy to grasp that when a plane is grounded for maintenance it can not be in the air to provide aerial support in case of a conflict. Using the old coating applied on F-16's and previous generation fighters the coating would be applied in multiple layers and needed frequent re-coating in order to stay operational. With the development of the fiber mat for the F-35 Lockheed claims that this maintenance is no longer needed due to the fiber mat smoothening out during its lifespan. And since the fiber mat has a lifespan which exceeds the lifespan of the F-35 itself no major maintenance has to be done to this part of the aircraft [17]. However in practice it turns out the aircraft for every hour of flight needs 9 man hours of maintenance [18]. Most of this maintenance time can be allocated to the electrical and hydraulic systems present in the aircraft with the modern fighters [17]. A further reduction of maintenance on the plane, thus, must be achieved by reducing the maintenance times on the systems mentioned above, which is out of the scope of this research.



Fig. 8: 6th generation aircraft of resp. US and China

5 DISCUSSION: FUTURE RESEARCH

The future of stealth is unsure, currently the United States as well as China are developing their 6th generation fighter aircraft (Figure 8) which operate mostly autonomous and have the ability to communicate with other aircraft, combine their radars and search for targets. This would imply that in order to successfully stay hidden from enemy radar all radar waves would have to be absorbed instead of bounced back in different directions. In order to allow this new types of material would most likely be developed with which the RL is of such high proportions the aircraft can stay undetected. Although hard to track as ordinary citizens this is still an interesting subject to keep track off over the coming years and maybe even decades since it would be of high importance for a nation to conduct operations in a stealthy way to prevent expensive losses.

With the improvement of stealth the radars in use are also pushed for improvements to better detect these stealth aircraft.

A good example of this is the downing of a Russian Su-35s, Russia's newest aircraft in late March 2022 [20]. It was speculated that the radar on this 5th generation aircraft was delivered to NATO countries in order to obtain the frequencies the Russians use on their radar, and possibly test this against their own stealth aircraft to see how they fare.

For an understanding on how coatings work the equation provided in Equation 1 gives a good image of the important parameters of stealth aircraft. However, using this equation only the situation as shown in Figure 7 can be calculated whilst most fighter aircraft make use of sloped planes on their planes. Which would nullify the equation provided for a radar wave that does not hit the aircraft on a 90° angle.

In order to compensate for this factor an added term would have to be included that can factor the angle into the equation.

6 CONCLUSION

Since its first developments in the 1930's stealth has had countless improvements. The first iterations of stealth aircraft only made use of reflective surfaces that would emit radar waves in all but the direction of the radar receiver. However with a growing in understanding how stealth technology would work coatings were developed which possess high energy surfaces that can dissipate the radar waves within the coating. When it concerns parameters that influence the performance of stealth aircraft, properties such as complex permittivity, complex permeability and intrinsic impedance are properties which influence the amount of absorbed radar energy in the coating applied on the outside of a plane. This relation was demonstrated in Equation 1.

Most recently Lockheed has developed a fiber mat which removes maintenance on the stealth aspect of the plane allowing for maximal air-time for the newest generation of fighters. For this fiber mat the equation no longer holds and actual numbers on absorption are highly classified thus impossible to obtain. With the technological push happening in this field it would not be unthinkable that the small RCS's the planes have now, will be reduced to having no RCS at all in the coming decades.

To reach this goal the fiber mat will have to be developed further or a new type of coating has to be developed which has enough surface energy to absorb all radar waves that touch the surface of the plane.

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